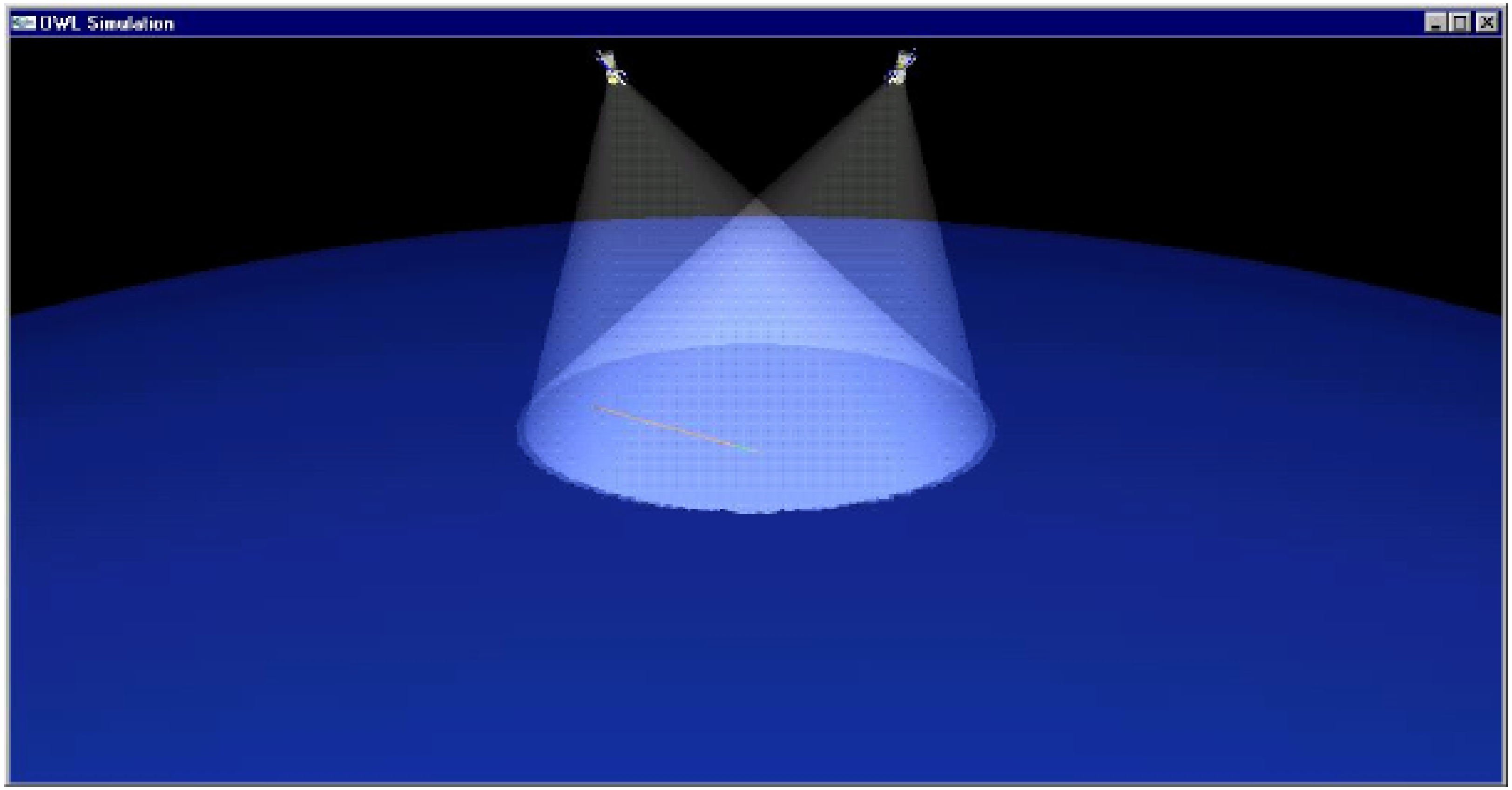
The **O**rbiting **W**ide-angle **L**ight-collectors Experiment

http://owl.gsfc.nasa.gov/



John Krizmanic

USRA/NASA/GSFC Code 661

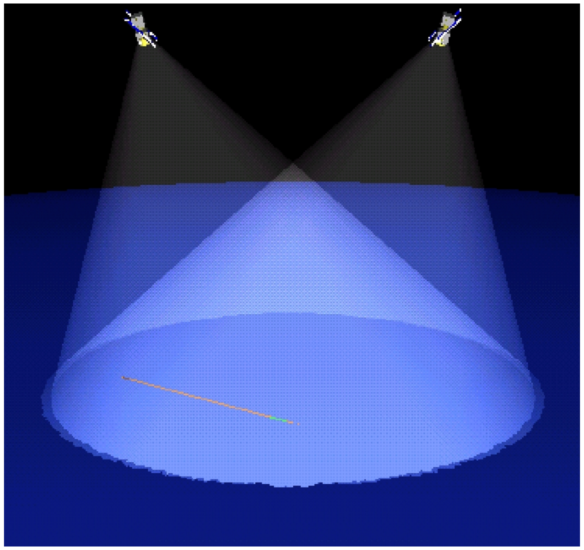
for the OWL Collaboration

The OWL Collaboration

NASA GSFC Laboratory for High Energy Astrophysics
University of Utah
University of Alabama, Huntsville
NASA MSFC
UCLA
Washington University
Columbia University
Vanderbilt University
Rutgers University
Montana State University

Outline:

- The OWL Concept
- OWL Baseline Design
- OWL Simulation Results
- Neutrino physics with OWL



The OWL Concept

Use air fluorescence technique to image 300 → 400 nm photons in ~ 0.06^{O} pixels (with 100 ns readout), from low Earth, equatorial (5 - 10^{O} inc.) orbits with wide angle (~ 45^{O} full, FOV) optics in a stereo configuration

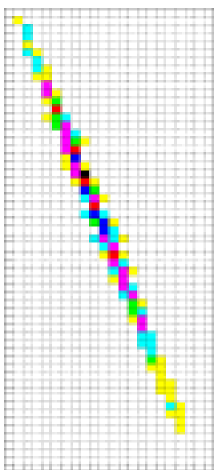
Start of mission 1000 km orbits → full, *instantaneous* aperture of 2 x 10^{6} km^{2}-ster for airshowers induced by $E \gtrsim 10^{20}$ eV cosmic rays

11.5% duty cycle → *effective* aperture 2.3 x 10^{5} km^{2}-ster

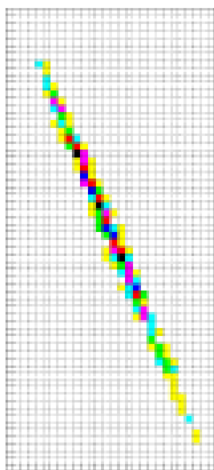
End of mission 550 km orbits → energy threshold ~ 3 x 10^{19} eV albeit with reduced aperture

Assuming Φ_{CR} (E) ~ $E^{-2.75}$ (AGASA extrapolation), the asymptotic OWL stereo aperture leads to ~ 2300 events/year with $E \geqslant 10^{20}$ eV

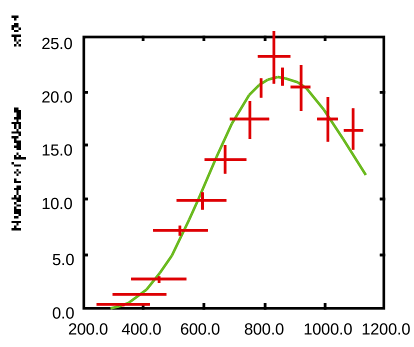
Assuming Φ_{CR} (E) ~ $E^{-3.0}$ (HiRes extrapolation), the asymptotic OWL stereo aperture leads to ~ 750 events/year with $E \geqslant 10^{20}$ eV



Eye 1



Eye 2

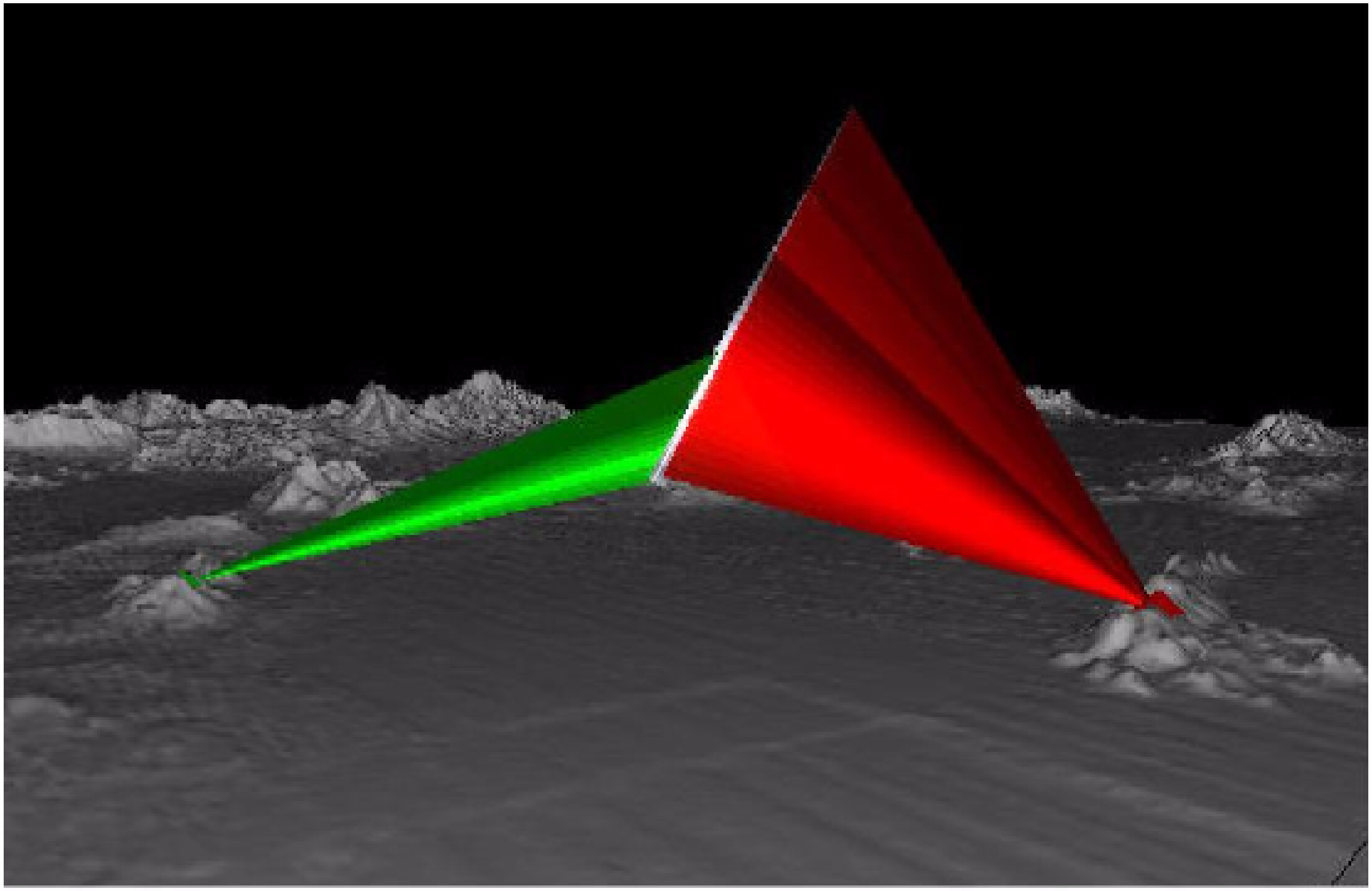


Flys Eye Collab. (G. Loh)

Motivation for a Stereo Detection

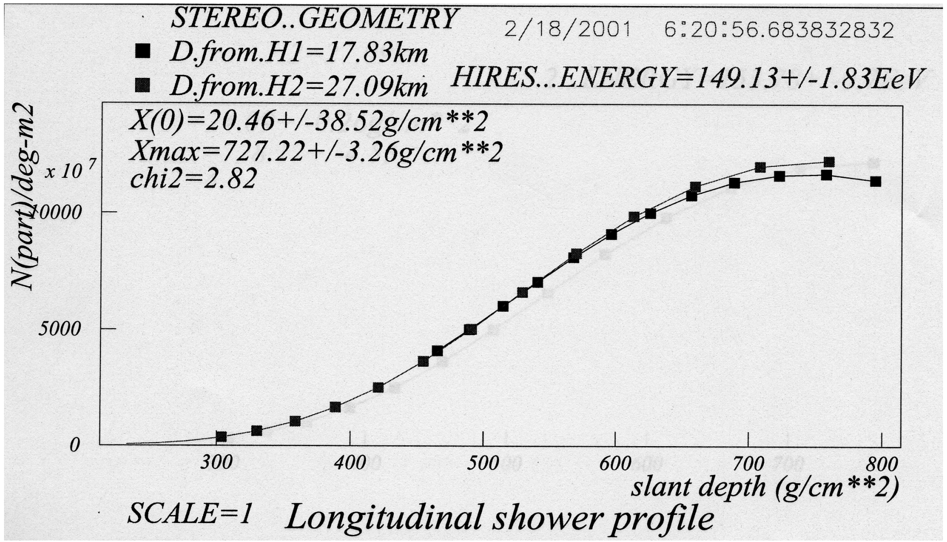
- Stereo system views airshowers from two different directions, providing redundancy and the ability to unambiguously determine heights in the atmosphere.
- Stereo viewing maximizes the capability to isolate external influences (i.e. distortion of shower profile by clouds, surface light sources, light generated by cosmic rays at the detector and albedo light).
- Stereo viewing provides constraints that reduce non-Gaussian errors in energy and angular determination.

HiRes Stereo Event

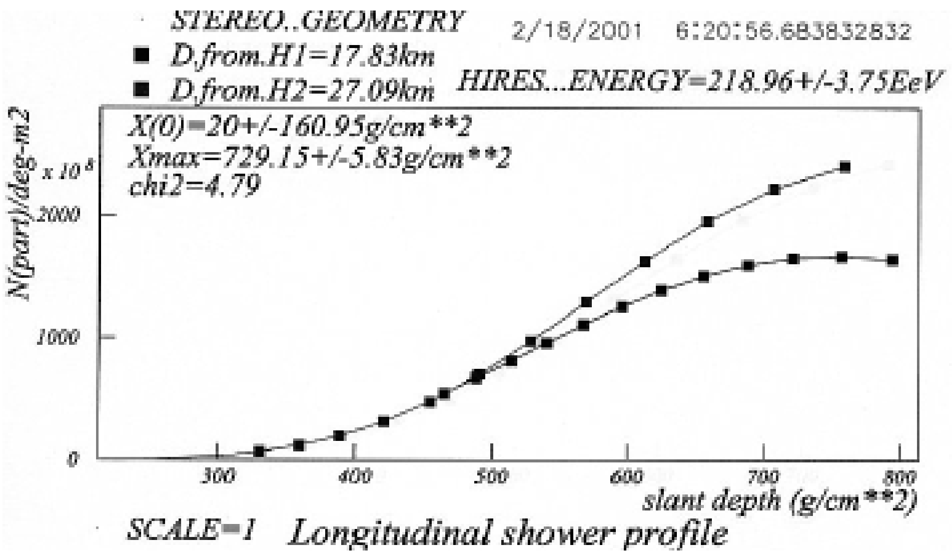


HiRes Collaboration (P. Sokolsky)

HiRes Reconstructed Stereo Event



$\lambda_{\text{Aerosol}} = 22.5$ km



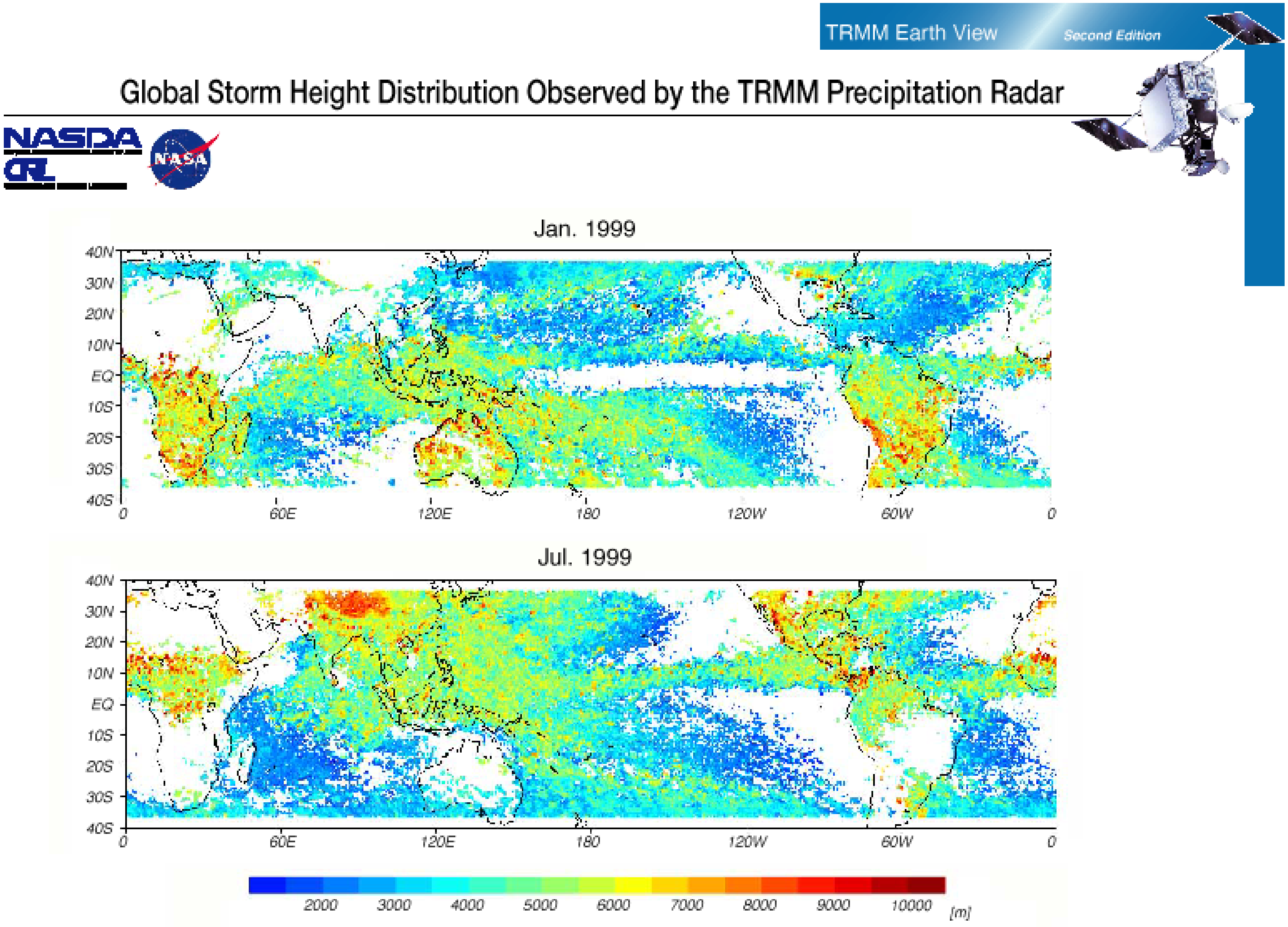
$\lambda_{\text{Aerosol}} = 12.5$ km

HiRes Collaboration (P. Sokolsky)

City Lights at Night

Defense Meteorological Satellite Program (DMSP)

Mid-Latitude Cloud Cover



rbiting
ide-angle
ight-collectors

OWL Instrument Baseline

Jan 7 - 18, 2002 : Complete/Review detailed instrument design at GSFC

- Finalized optical design
- Mechanical and deployment designs
- Focal plane and electronics design
- Mass and power specifications

Jan 22 - 25, 2002: Completed detailed mission study at GSFC

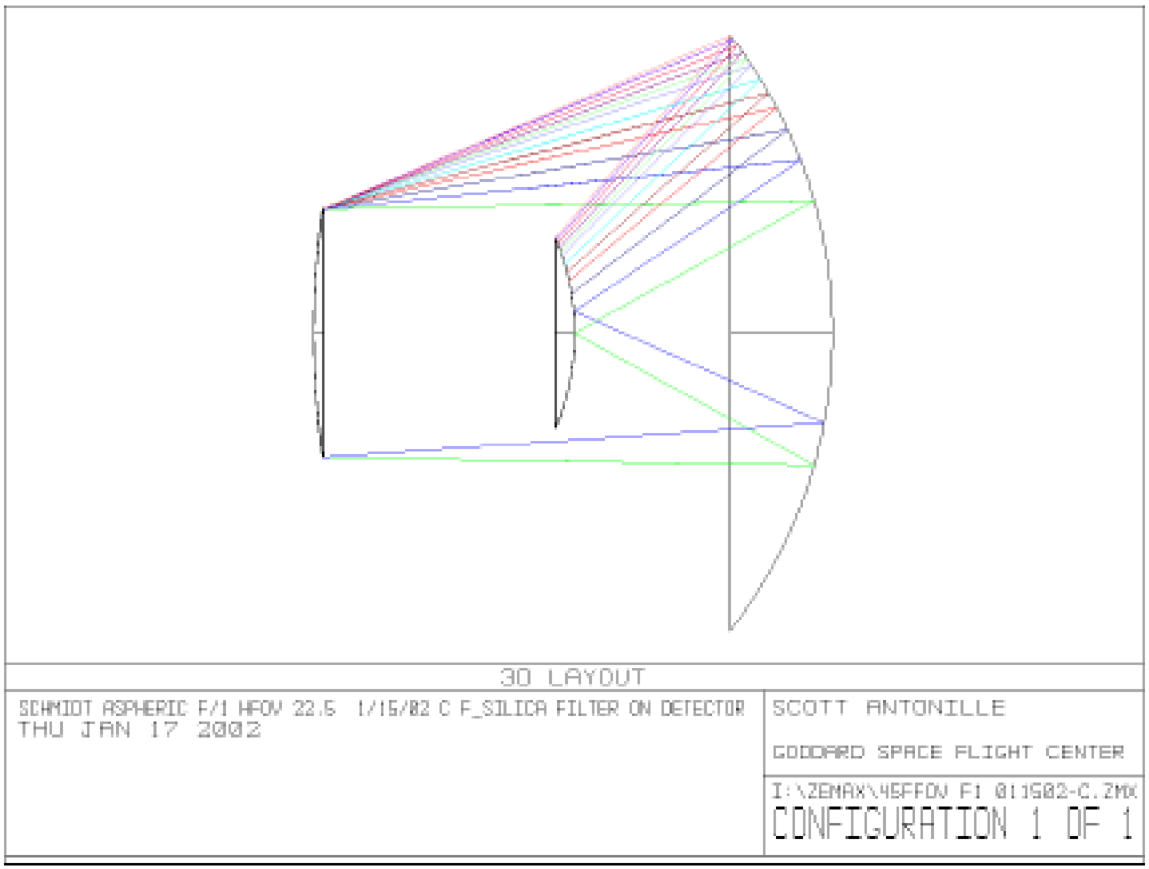
- Develop mission profile using pointing and formation flying requirements
- Specified spacecraft and systems to provide necessary performance

Mission is completely feasible with no ‘tall poles’ identified or enabling technology development required

rbiting ide-angle ight-collectors

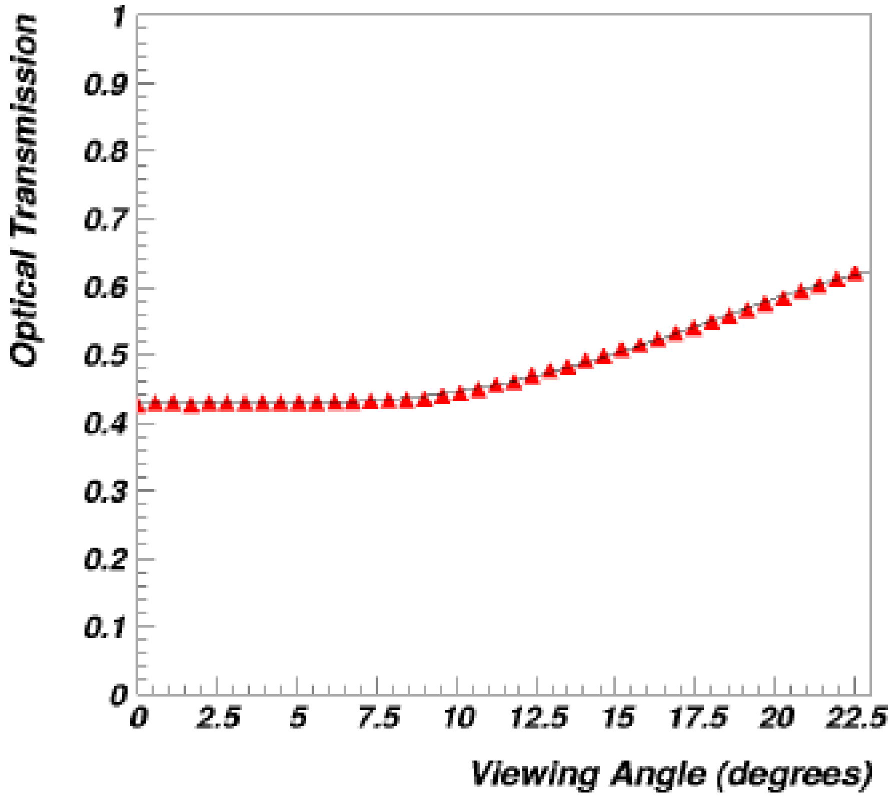
OWL Baseline Schmidt Optics

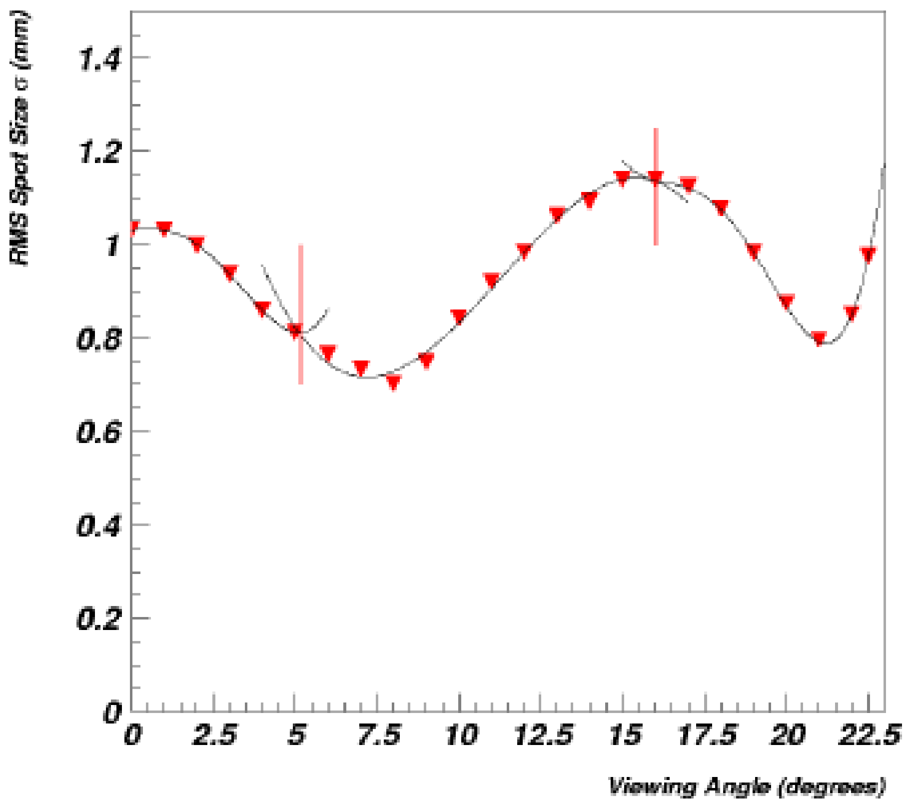
0.06^{o} Pixel Angular Resolution in UV
~ 10^{4} away from Diffraction Limit



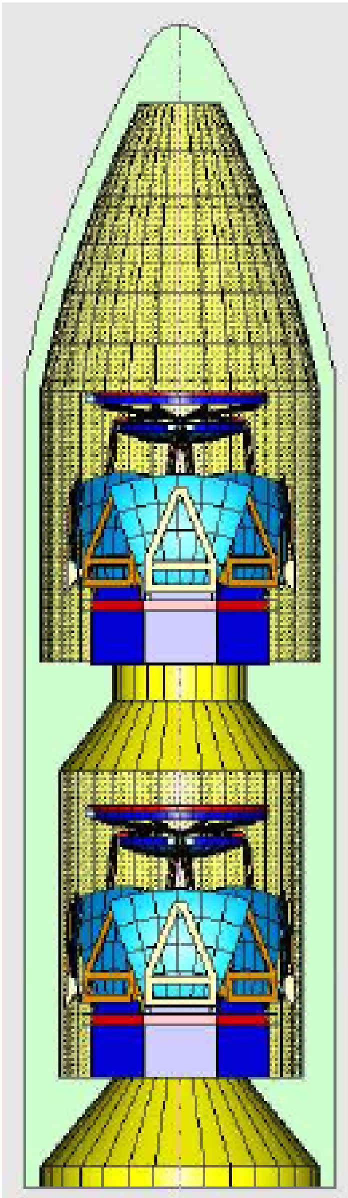
- F/1 System
- 3.0 m Diameter Optical Aperture formed by Single Corrector Plate
- 7.1 m Diameter Aspherical Mirror
- 2.3 m Diameter Focal Plane
- Full FOV 45^{O}
- 3 mm Focal Plane Pixel Diameter
- ~ 1 mm, 0.1^{O} Alignment

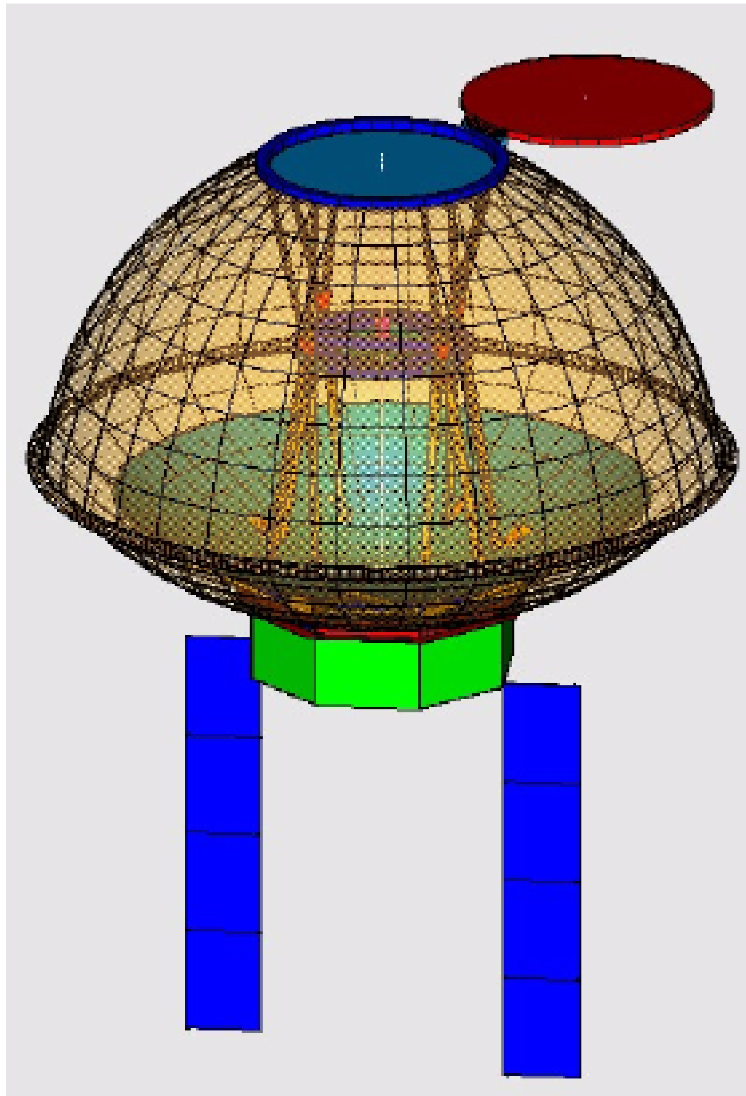
OWL Baseline Optics Performance

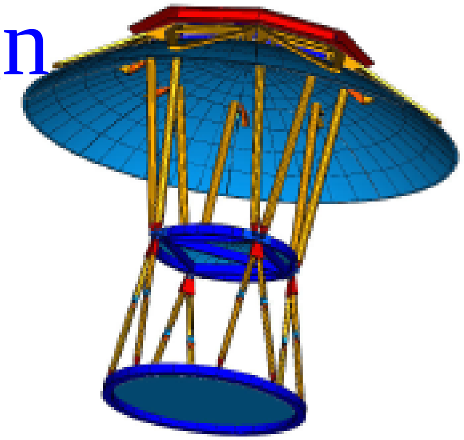


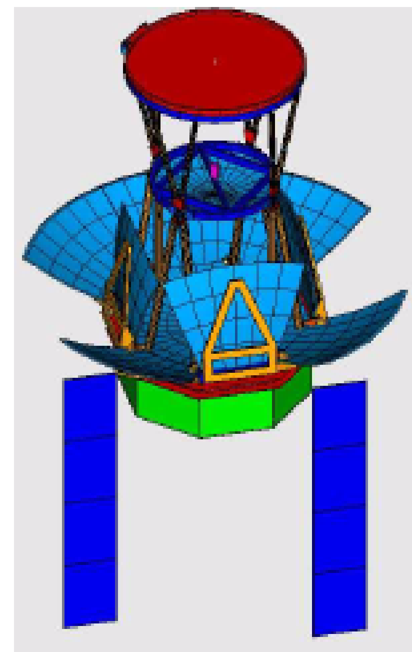


OWL Mechanical Design



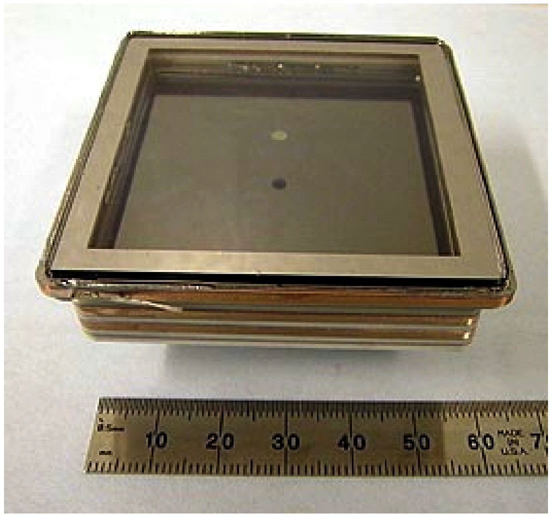






Rodger Farley et al., NASA GSFC

OWL Focal Plane



Prototype Burle 85001 low-profile microchannel-plate photomultiplier.

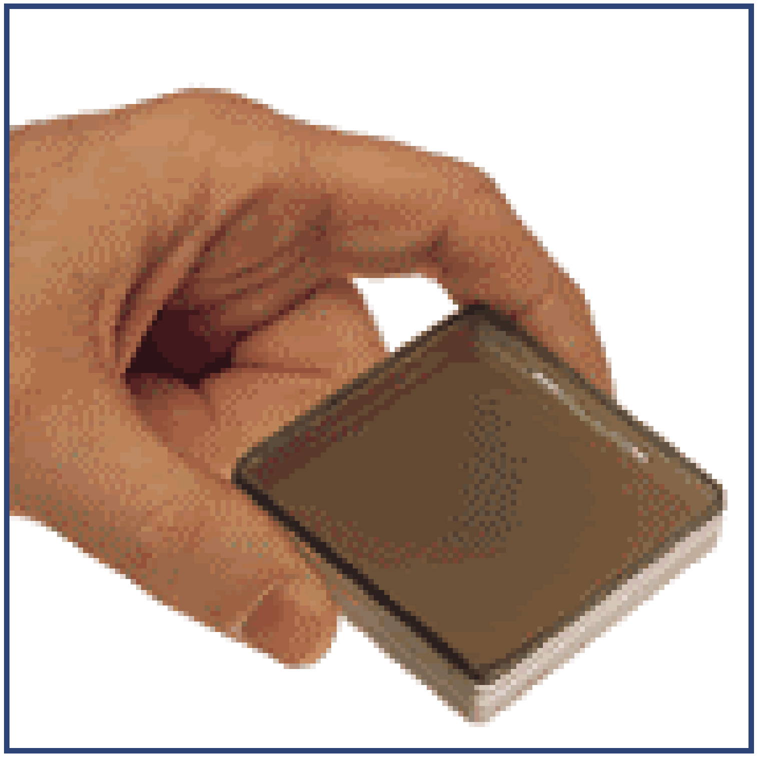
Focal Plane will employ Commercial Technology (Burle 85001 derivative, Hamamatsu flat panel)

- 2.3 m diameter Focal Plane formed by mosaic of multi-channel elements

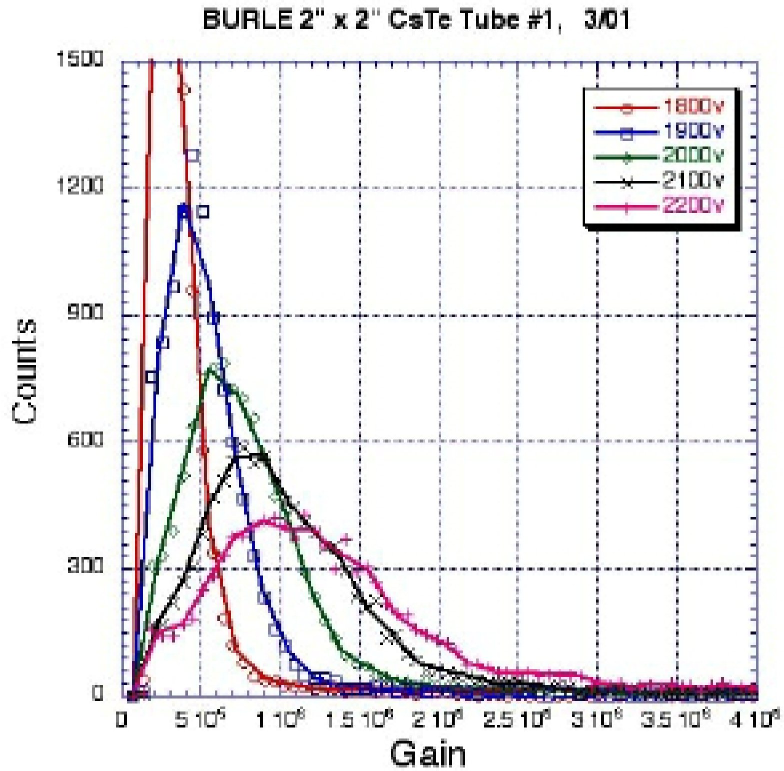
- ~ 400 channels per PMT (1 channel => 1pixel)
- ~ 6cm x 6cm square per PMT
- ~ 539,000 total channels
- =>1,348 PMTs (ie. 539K/400)

rbiting
ide-angle
ight-collectors

Burle 85001 Photomultiplier



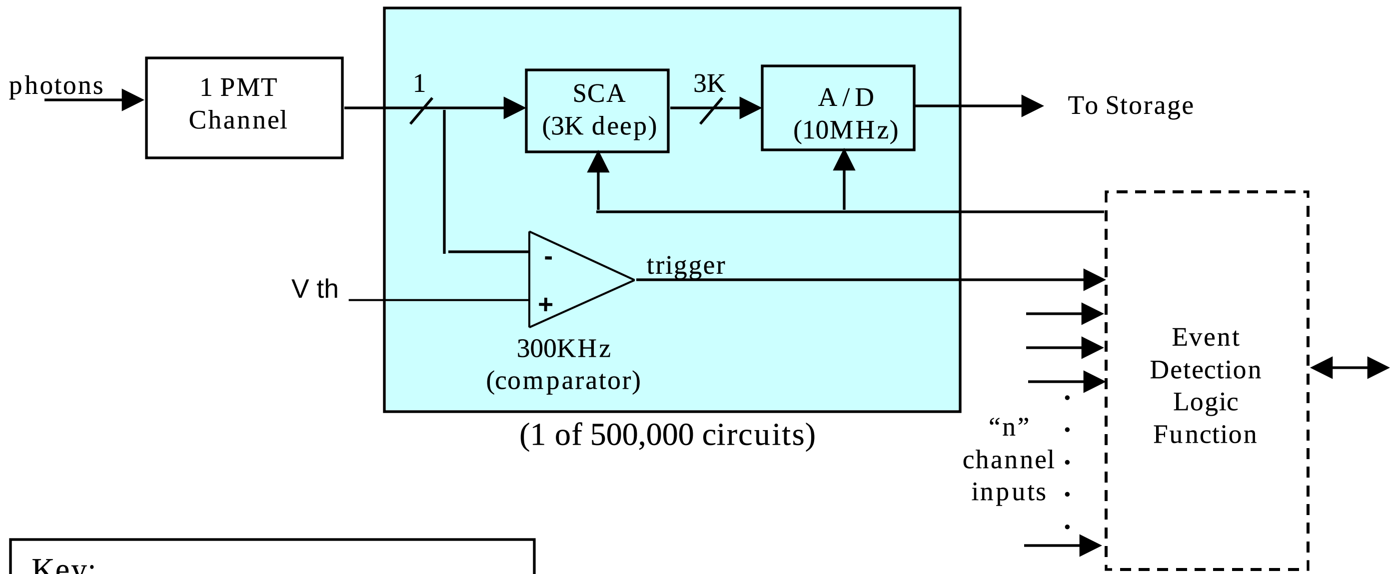
Prototype Burle low-profile microchannel-plate photomultiplier.



Single photoelectron peak resolved by Burle 85001 at various high-voltages.

OWL Readout Electronics

Electronics Design



Key:

PMT - PhotoMultiplier Tube

SCA - Switched Capacitor Array

J. Mitchell, GSFC

J. Smith, University of Utah

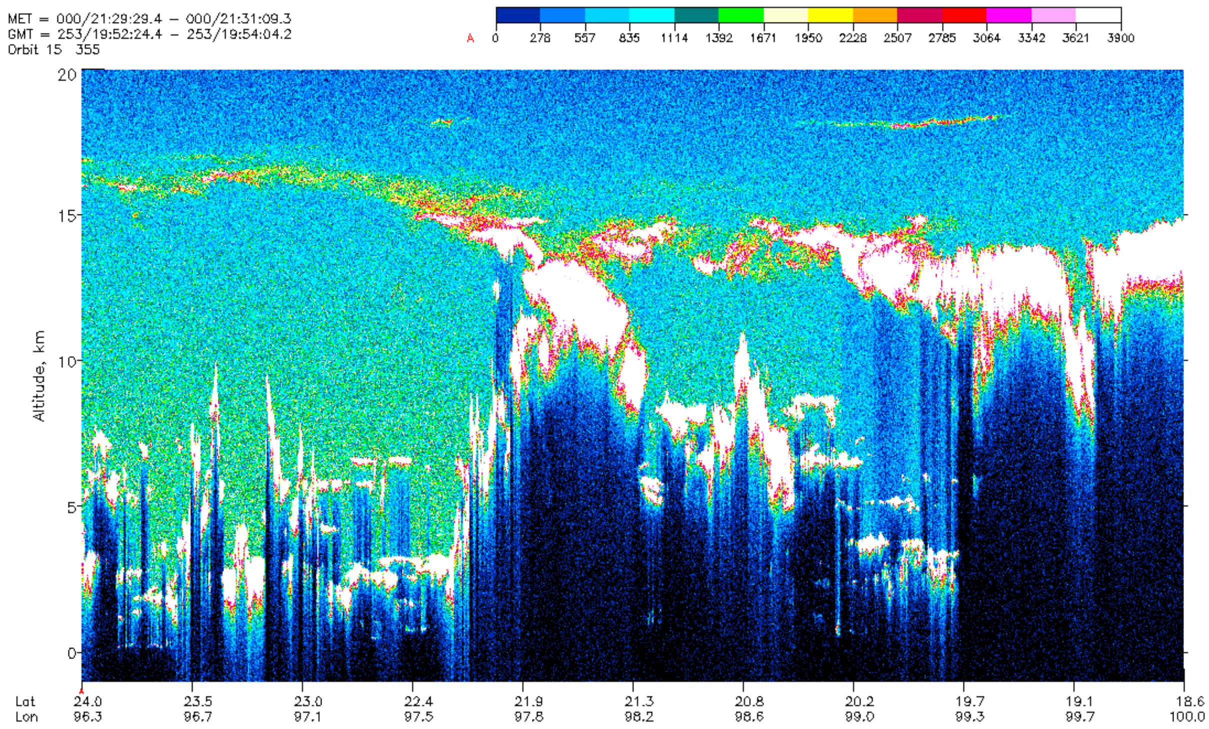
Focal Plane Detector and Electronics Power < 1000 W

Entire Spacecraft Power < 1000 W

Cloud Monitoring

LITE Image for 355 nm Wavelength - Orbit 15

Lidar In-space Technology Experiment http://www-lite.larc.nasa.gov/



Controlled pointing Lidar system on each OWL eye

• ~ 10 mJ/pulse sufficient power

• Laser transmitter similar to that in Geoscience Laser Altimetry System (GLAS) mission (Dec. 02 launch)

• OWL focal plane detector used

• GOES (IR) measurements identify optically thick clouds on 15 minute basis

Modeling Procedures (Airshowers)

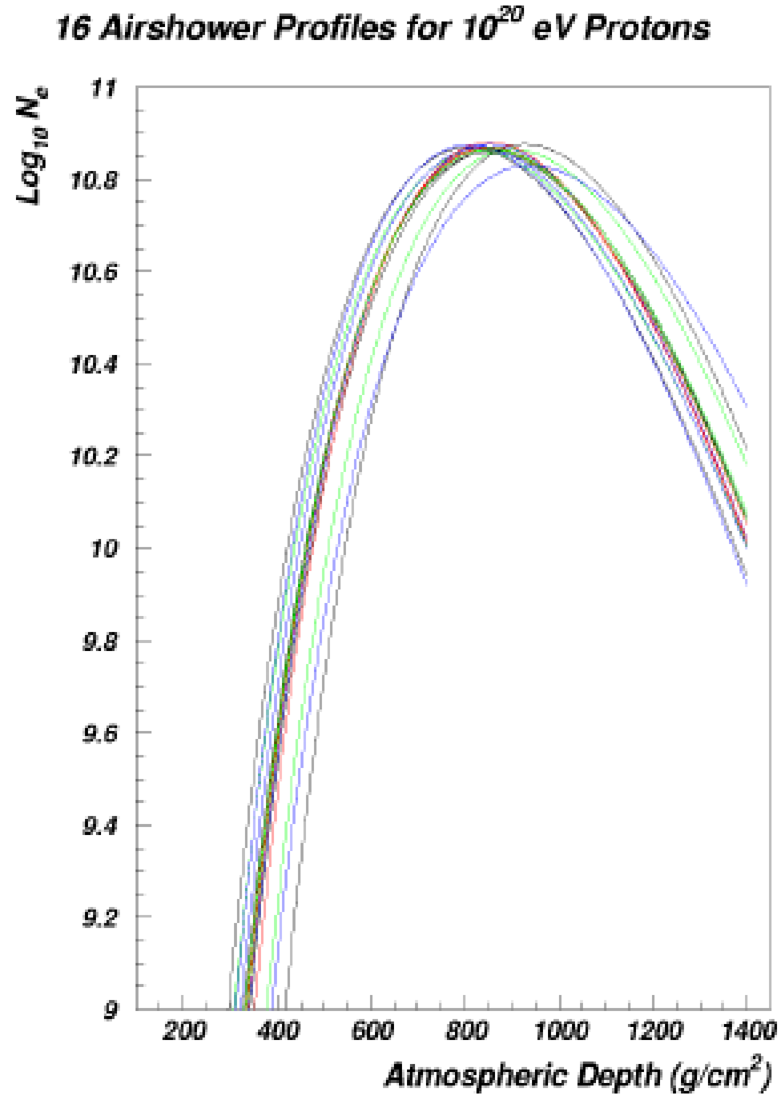
Airshower Event Generator

Employs generator developed by Paul Mikulski (USNA) which models hadronic primaries interacting with the Earth's atmosphere generating longitudinal airshowers (see Paul's Ph.D. thesis, JHU):

- A variation of the Hillas splitting algorithm
- Charged pion decay and neutral pion re-interaction
- A parameterization of the LPM effect
- Shower starting point and development fluctuations
- Shower described by 4-parameter Gaisser-Hillas function

Basic Assumptions

- Isotropic flux impinging on spherical Earth
- Shibata Parameterization of Atmospheric Grammage
- Standard 1976 US Atmosphere temperature profile
- Fluorescence and Cherenkov includes λ dependence
- Shower generated and signals recorded in 1 μs steps



Modeling Procedures (Light Generation)

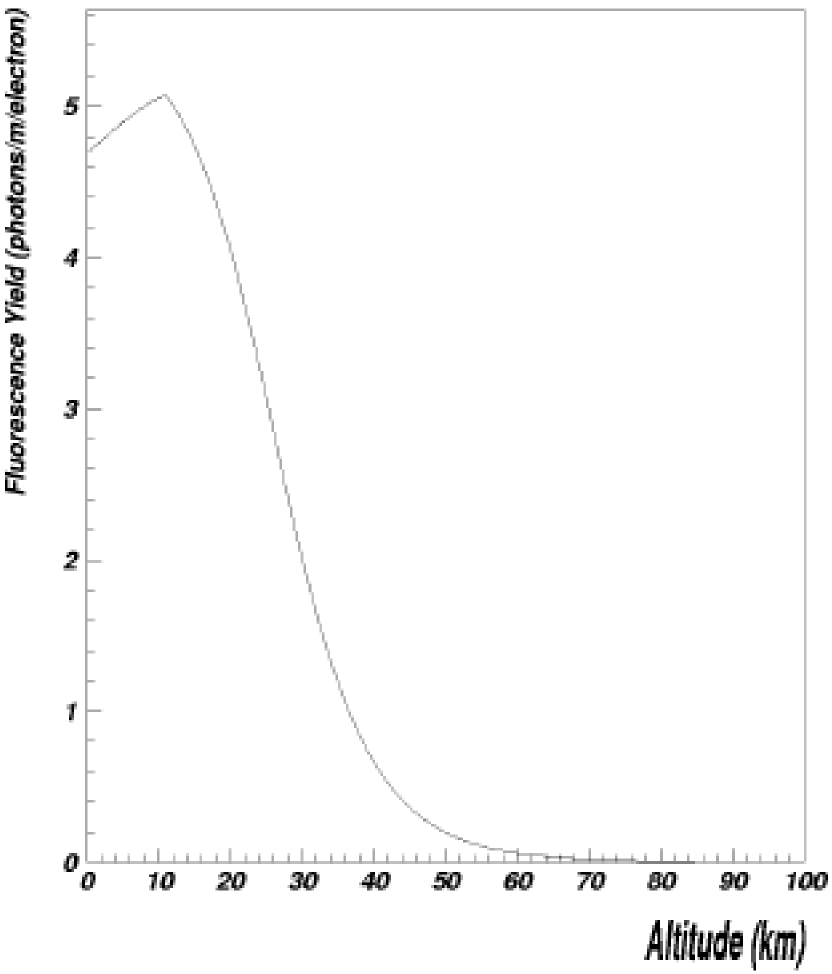
Signal Generation

• Fluorescence λ dependent (Bunner, Ph.D. thesis) with pressure and temperature dependence (Kakimoto et al., ICRR-Report-346-950-12)
• Cherenkov light generated in 25 nm bins for 200 nm -> 600 nm. Light scattered into instrument via (Baltrusaitis et al., NIM A240)

$$d^2N/dl\, d\Omega = dN/dl\ 3/16\pi\ (1 + \cos^2(\theta_{View}))$$

UV Background

Modest DC Dark sky background assumed

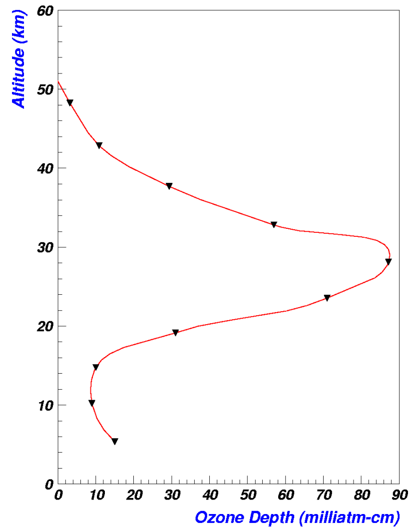


rbiting
ide-angle
ight-collectors

Modeling Procedures (Atmospheric Scattering)

Atmospheric Scattering of Light

Slant depths to instrument(s) calculated point-by-point on shower path numerically. Fluorescence and Cherenkov signals attenuated with implicit λ dependence:



Rayleigh Scattering:

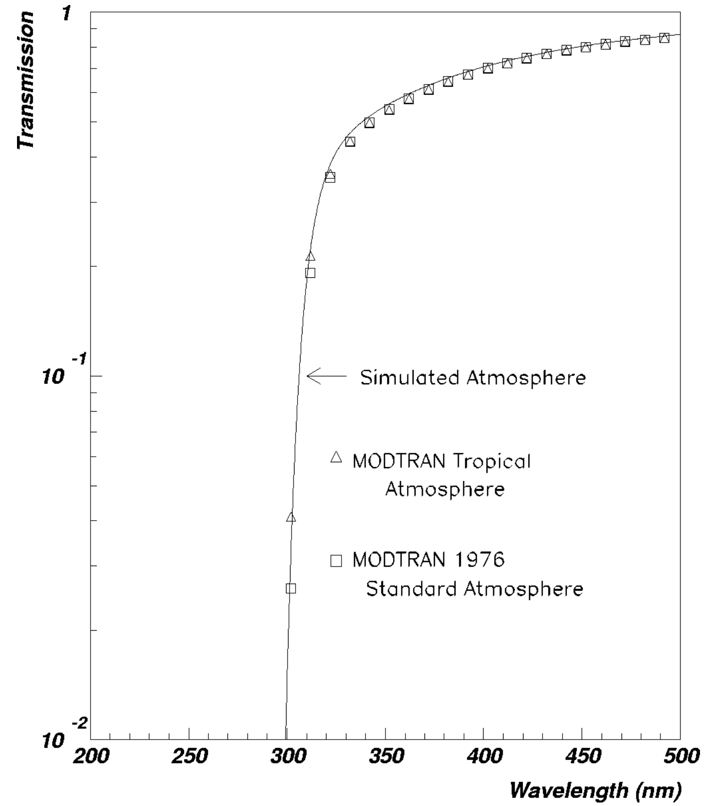
$dN_\gamma/dx = -\rho\ (N_\gamma/\{X_R)(400/\lambda)^4$

where X_R =2974 g/cm^2 and λ in nm

Ozone Absorption: (McPeters et al.)

$dN_\gamma/dx \sim \exp(-0.325\ \kappa)$

$\kappa = 10^{110.5\ -\ 44.21\ \log\lambda}$ (atm-cm)$^{-1}$ and λ in nm



Effects not presently included:

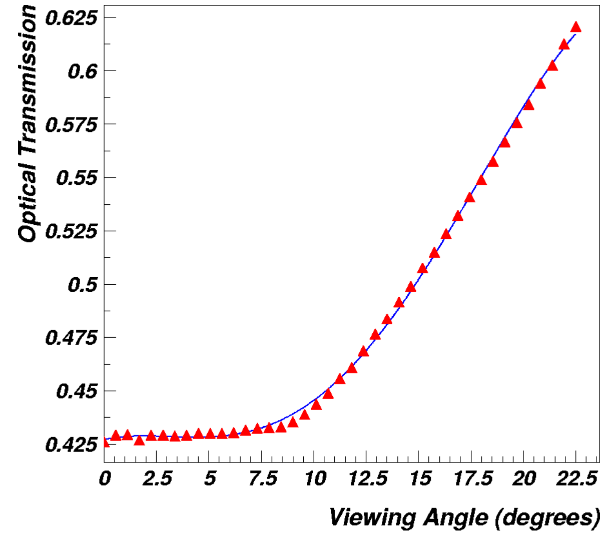
- Mie (aerosol) Scattering: At Earth's surface ~ $\exp(-h/h_0)$ with h_0 ~ 1 km
- Clouds, volcanos, fires, etc

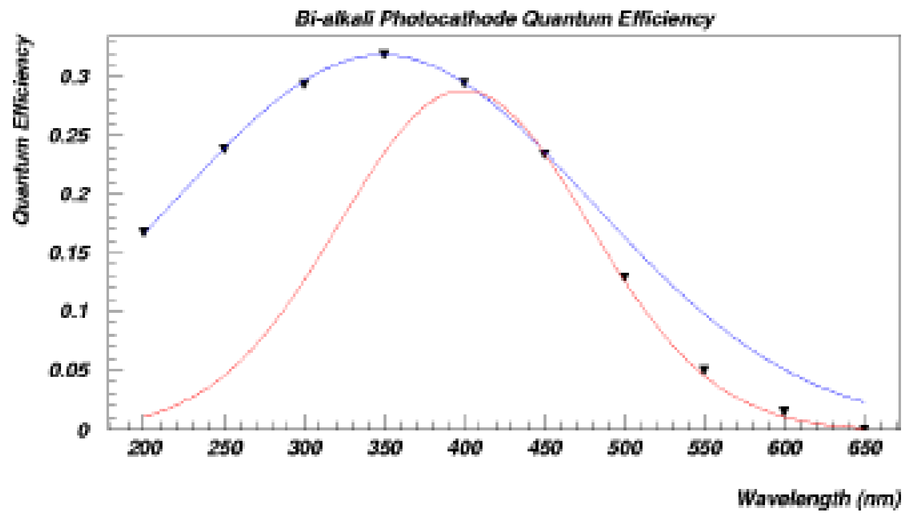
At this point, the UV signal has been transported out of the atmosphere and delivered to the instrument.

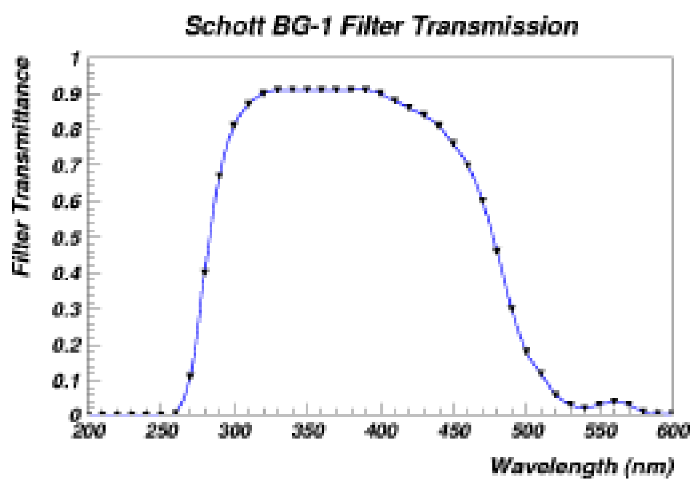
Model Procedures (Instrument, Schmidt Baseline)

Basic Assumptions

- Wide FOV Optics with 7.1 m^2 Optical Aperture (S. Antonille, internal OWL notes)
- BG-1 UV filter
- Bi-alkali photocathode (Philips PMT Data Handbook)
- Light spot size assumed Gaussian with RMS diameter 0.7 - 1.15 mm ($f(\theta_{View})$)
- Pixel size of 0.06° (3 mm diameter) assumed
- Relative shower position (in angular pixel of 0.06°) mapped appropriately into relative focal plane pixel
- Gaussian spot is integrated for each pixel assuming a 95% live area and Poisson fluctuated to yield PE signal
- Trigger formed by summing individual pixel response over ~ 4 μsec



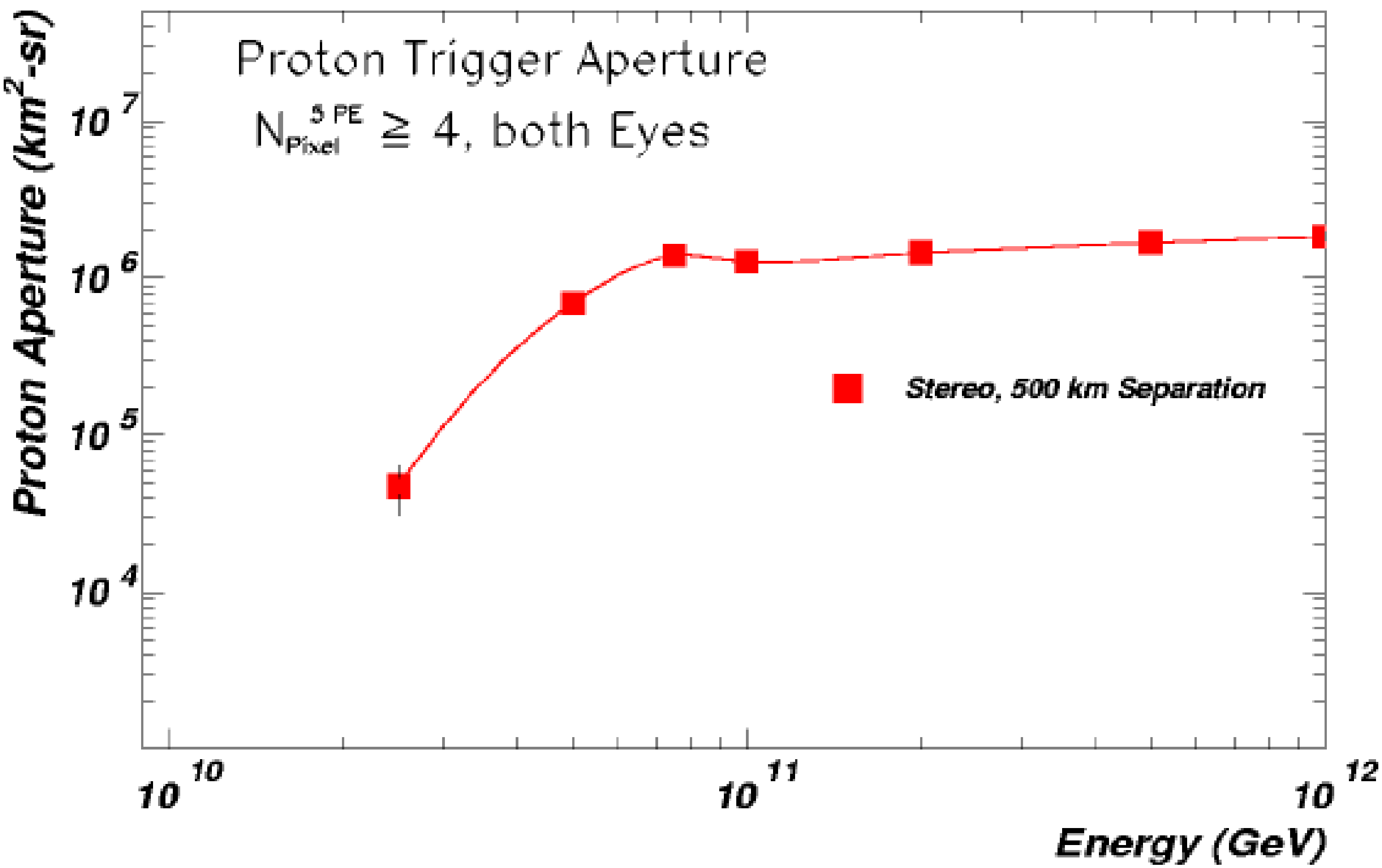




Orbiting Wide-angle Light-collectors

OWL Instantaneous Proton Aperture

Schmidt Optics, 1000 km Orbits

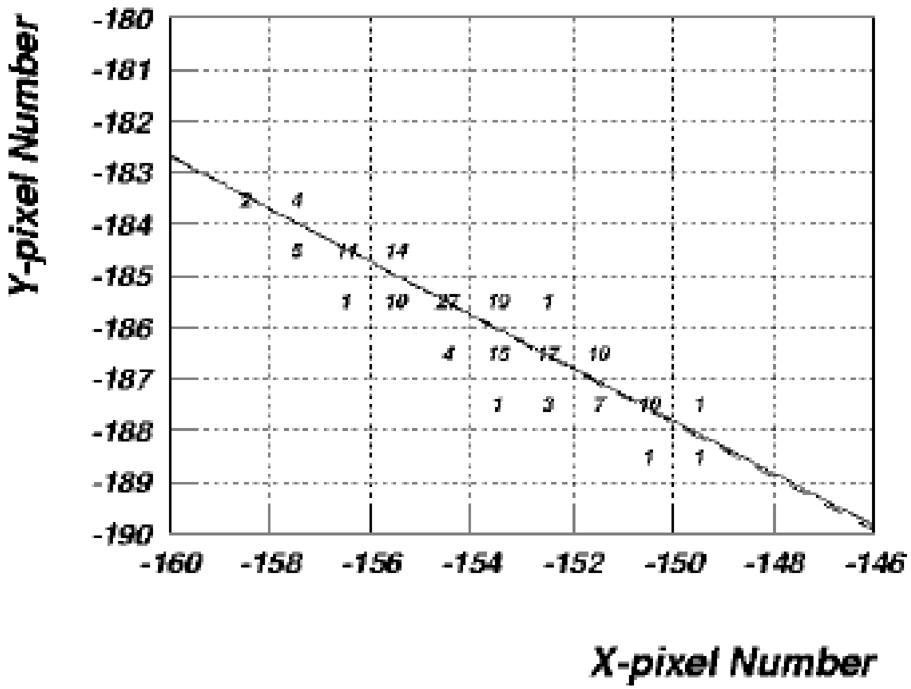


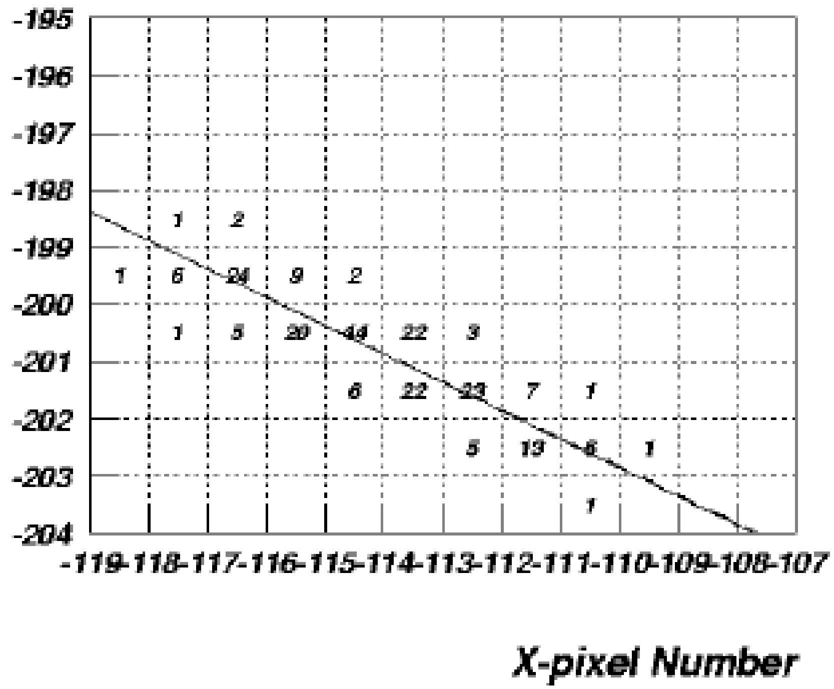
Trigger criteria yields 35 Hz in focal plane (at Level 1trigger) from UV dark sky background (400 γ/nsec/m^2/ster)

Orbiting Wide-angle Light-collectors

OWL 10^{20} eV Proton Simulated Event

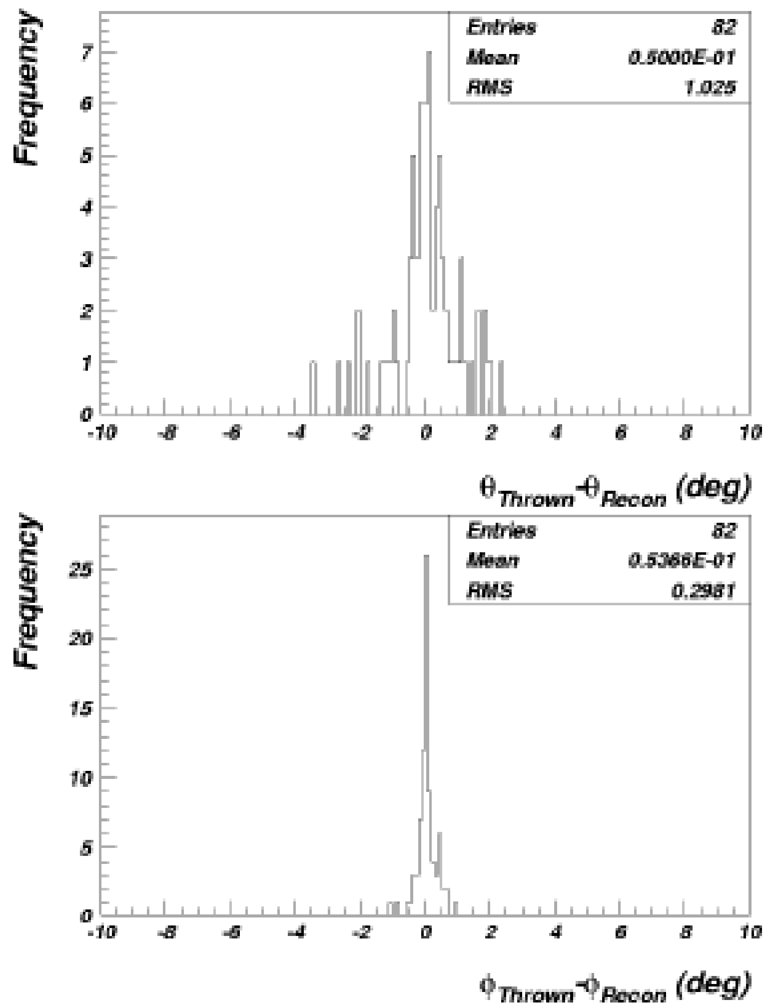
1000 km Orbits, 500 km Satellite Separation





Reconstruction Selection

1000 km Orbits, 500 km Satsep, 2 x 10^{20} eV Protons



Use stereo reconstruction on integral track lengths to determine angular resolution

Yields lower limit on event acceptance as timing fits will provide additional information

Selection criteria

- Angle between reconstructed normal vectors

  $\gtrsim$ 7 deg

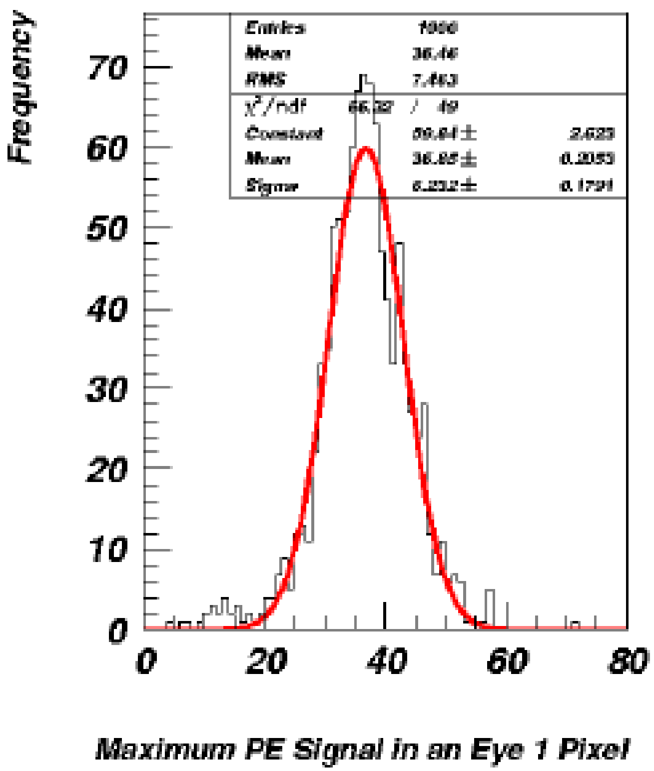
- Focal plane track length in each instrument

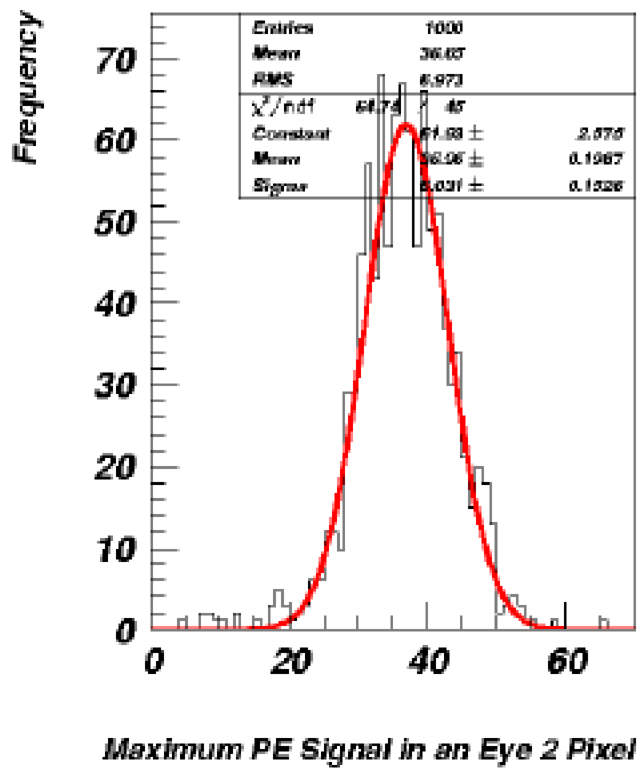
  $\geqslant$ 9 pixels

rbiting
ide-angle
ight-collectors

Inherent Energy Resolution

Fixed shower throwing point and incident angles (E =10^{20} eV)





1000 km orbits, 500 km satellite separation

Throwing point directly between satellites (x=y=0), θ=45^{o}, φ=90^{o}

Energy resolution will be dominated by shower fluctuations

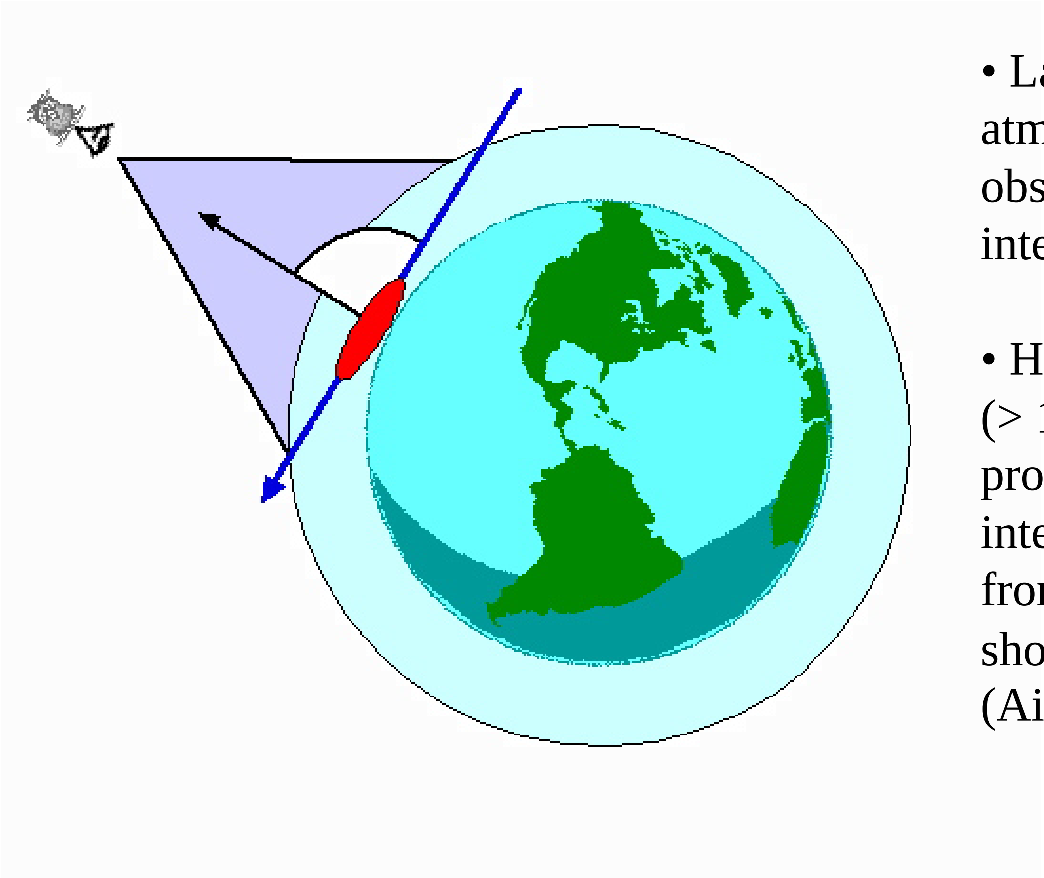
Total PE distributions demonstrate similar resolution

	HiRes	Auger Ground (Hybrid)	EUSO 1 ISS Instrument	OWL 2 Satellites
Status	Running	Under Construction	Study Phase	Study Phase
Energy [(1)] **Range (eV)**	10^{17} - 4 x 10^{20}	10^{19} - 10^{21}	3 x 10^{19} – 3 x 10^{21}	~ 3 x 10^{19} – 8 x 10^{21} E_{thres} @ 550 km Orbits
Incident θ Resolution	0.6^{O} (E = 10^{18} eV)	1.3^{O} (0.3^{O}) (E = 10^{20} eV)	0.2^{O} - 3^{O}	0.2^{O} - 1^{O}
Energy Resolution	< 20% (E = 10^{18} eV)	25% (10%) (E = 10^{19} eV)	< 20% (E = 10^{20} eV)	~ 15% (E = 10^{20} eV)
Instantaneous **Aperture (km^2-ster)**	10^4	7000 /site	5 x 10^5	2 x 10^6 @ 1000 km Orbits
Duty Cycle	10%	100% (Hybrid 10%)	10%	11.5%
Effective **Aperture (km^2-ster)**	1000	7000 /site (700 /site (hybrid))	50,000	230,000
# Evts E > 10^{20} eV ($\varphi \sim E^{-2.75}$)	10/year 100 (10 years)	70 (7 hybrid)/site/year 700/site (10 years) 70/site hybrid (10 years)	500/year 1500 (3 years)	2300/year 11,500 (5 years)
# Evts E > 10^{20} eV ($\varphi \sim E^{-3}$)	3/year 30 (10 years)	23 (2 hybrid)/site/year 230/site (10 years) 23/site hybrid (10 years)	170/year 510 (3 years)	750/year 3750 (5years)

(1) The upper limit is defined as the energy where 1 event/year is observed as determined by the experiment's aperture and assuming a differential spectral index of -2.75

UHE Neutrinos via Air Fluorescence

3rd OWL UCLA Neutrino Workshop Feb. 2002



• Large Aperture (10^{12} tons of *effective* atmospheric target) opens the door for observing ultra-high energy neutrinos interactions

• Horizontal Airshowers initiated deep (> 1500 g/cm^2) in the atmosphere provide a signature of neutrino interactions which are well-separated from hadronic and electromagnetic showers, $\lambda_\nu \sim 10^{10}$ cm, $\lambda_p \sim 10^4$ cm (Air, STP, E = 10^{20} eV)

Neutrino Induced Airshowers

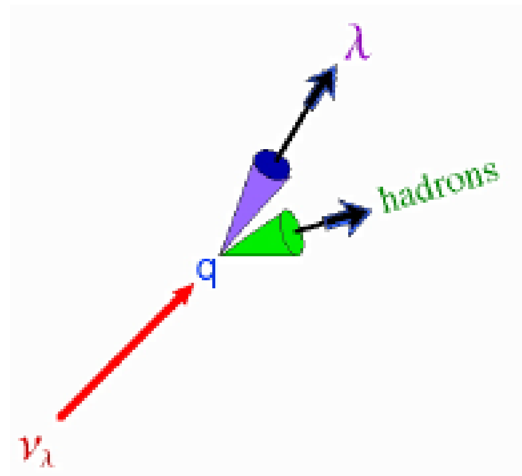
For UHE neutrino-quark interactions at 10^{20} eV,

$\sigma_{cc}(\nu N) = \sigma_{cc}(\nu N) = 5.5 \times 10^{-36} (E_\nu / 1\ \mathrm{GeV})^{0.363}$, $E_\nu > 10^{16}$ eV

$\langle E_\lambda \rangle \sim 0.8\ E_\nu$ – $\langle E_{Hadrons} \rangle \sim 0.2\ E_\nu$

Leptonic induced airshower properties:

- Electron: Electromagnetic Shower
- Muon: $E_{Critical} \sim 1$ TeV
- Tau: $E_{Critical} \sim 1$ PeV, ct = 87 μm -> For E_τ = 20 EeV, $\gamma c\tau$ = 1000 km



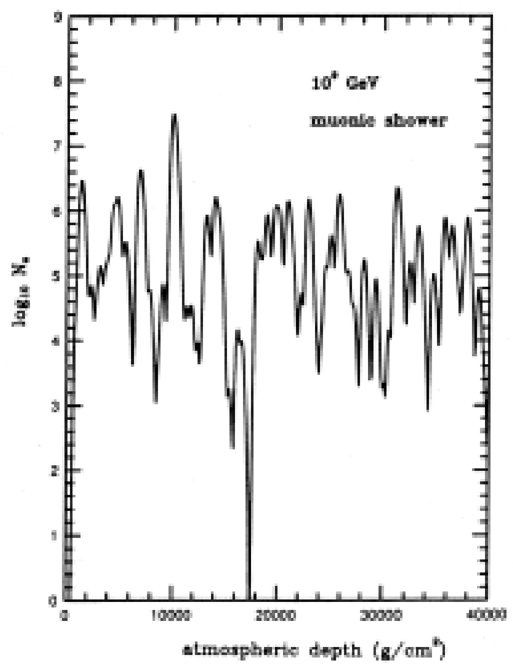
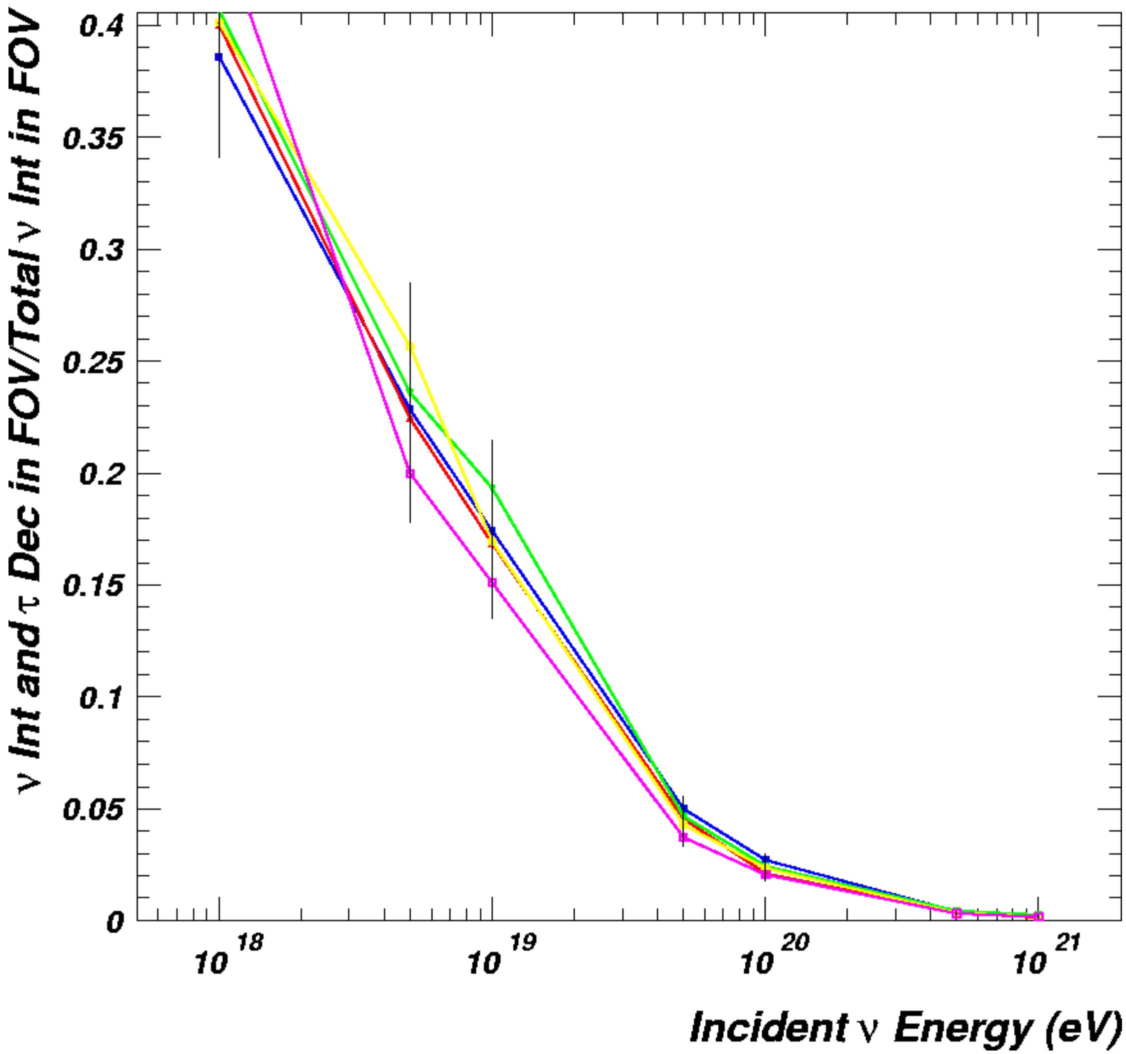


FIG. 2. A sample muon air shower. Shower size as a function of atmospheric depth. Muon energy 10^8 GeV.

Stanev and Vankov, Phys Rev D 40 (1989)

Interaction	$\langle E_\lambda \rangle / E_\nu$	$\langle E_{Hadrons} \rangle / E_\nu$	$\langle E_{Shower} \rangle / E_\nu$	$\sigma / (E_\nu / \mathrm{GeV})^{0.363}$
ν_e N -> e N’	0.8	0.2	1.0	5.53×10^{-36}
ν_e N -> ν_e N’	0.8	0.2	0.2	2.30×10^{-36}
ν_μ N -> μ N’	0.8	0.2	> 0.2	5.53×10^{-36}
ν_μ N -> ν_μ N’	0.8	0.2	0.2	2.30×10^{-36}
ν_τ N -> τ N’	0.8	0.2	> 0.2	5.53×10^{-36}
ν_τ N -> ν_τ N’	0.8	0.2	0.2	2.30×10^{-36}

UHE Atmospheric Tau Neutrinos

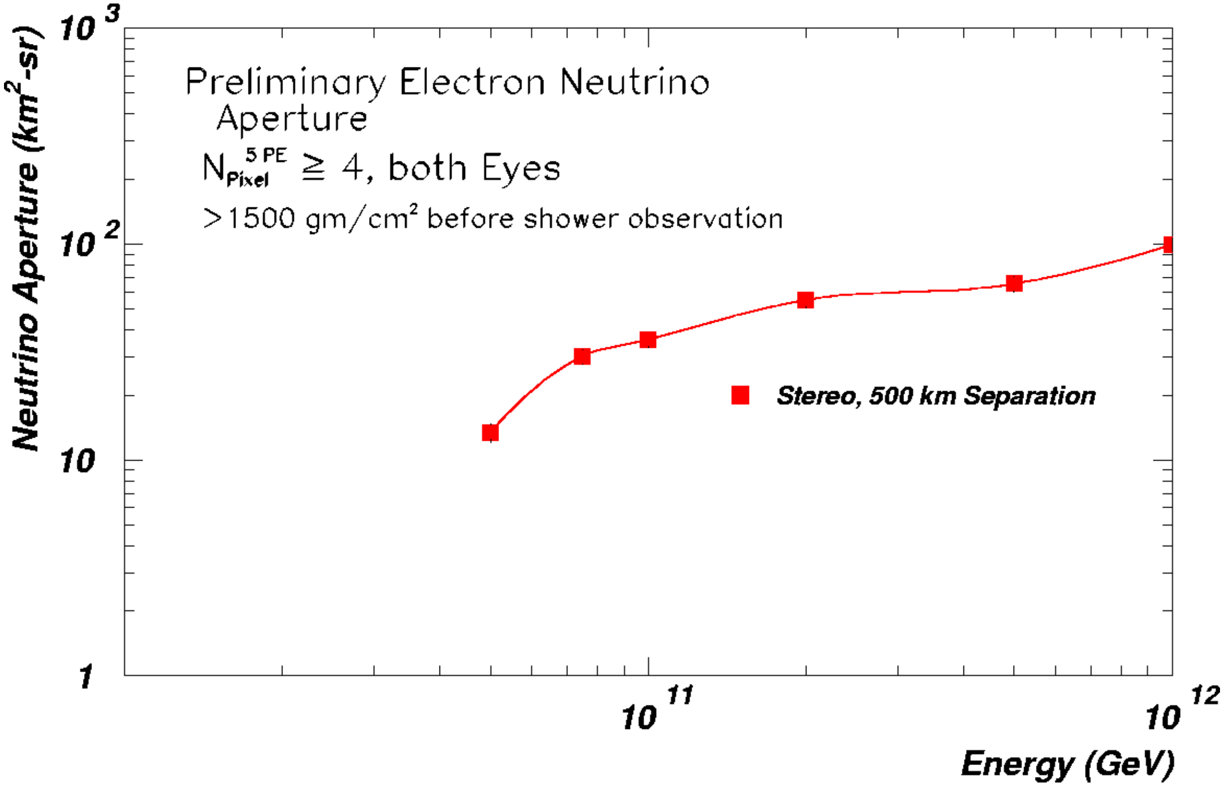


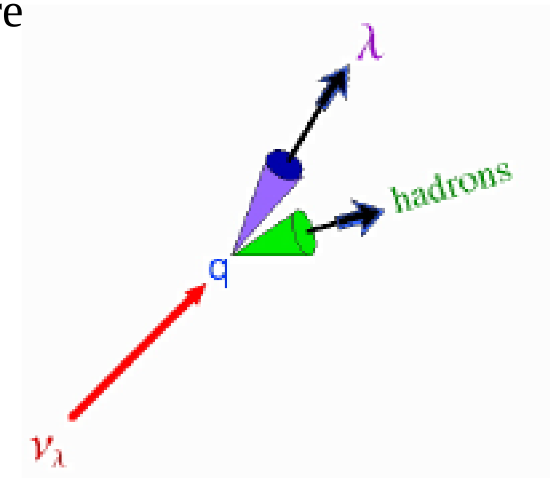
Is ‘double-bang’ of UHE ν_τ interaction and subsequent τ decay observable?

- τ energy loss not a large effect in the atmosphere(~ 10% for E_τ = 10^{20} eV, 1000 km in STP air; Dutta et al., hep-ph/0012350v1)

OWL Electron Neutrino Aperture

1000 km Orbits, Schmidt Baseline, Instantaneous Aperture





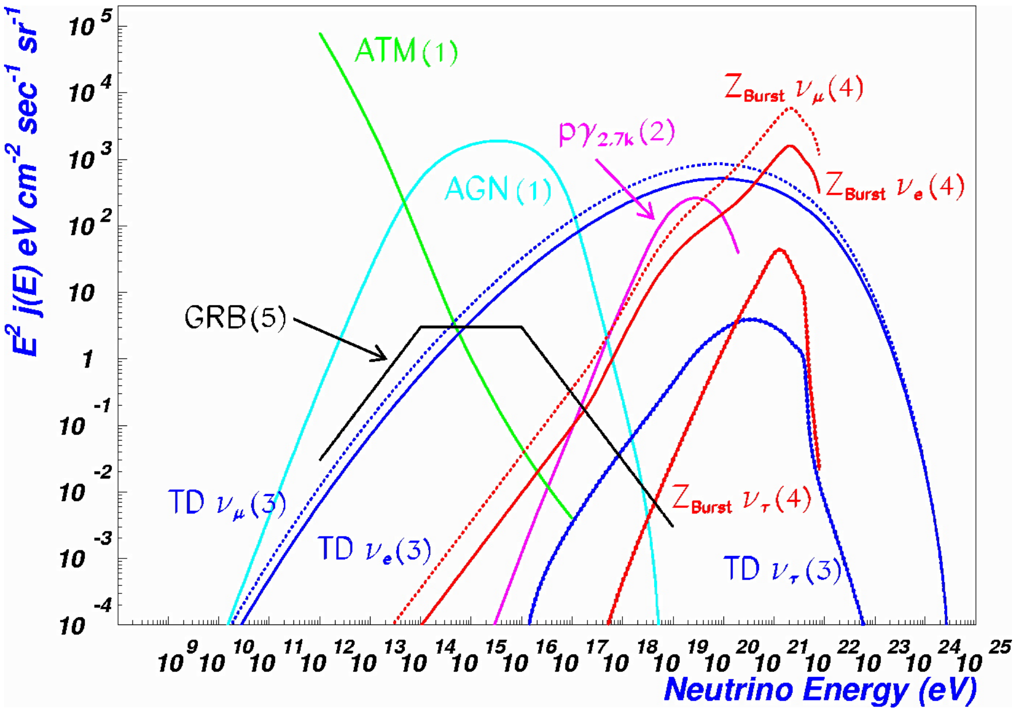
$\sigma(\nu N) = \sigma(\nu barN)$, $E_\nu > 10^{16}$ eV

For UHE ν_λ N -> λ N', on average 80% E_ν deposited into lepton.

For UHE ν_e N -> e N', 100% E_ν deposited into airshower

OWL Preliminary Electron Neutrino Event Rates

1000 km Orbits, 10% Duty Cycle, Schmidt Baseline



Interaction	Stereo 500 km Sat. Sep.
$p\gamma_{2.7K}$ (6)	0.1 – 0.4 Events/Year
Topological Defects (3)	12 Events/Year
Z_{Burst} (4)	11 Events/Year
$E_{Threshold}$	$\lesssim 10^{20}$ eV

550 km orbits will yield reduction in energy threshold by factor of > 3

1 Stecker &Salamon, Space Sci Rev 75 (1996)
2 Stecker, Done, Salamon, &Sommers, PRL 66 (1991)
3 Sigl, Lee, Bhattacharjee, & Yoshida, Phys Rev D 59 (1998), $m_X = 10^{16}$ GeV, X -> q+ q, SuperSymmetric fragmention
4 Yoshida, Sigl, & Lee, PRL 81 (1998), $m_\nu = 1$ eV, Primary $\Phi_\nu \sim E^{-1}$
5 Waxman and Bahcall, PRL 78 (1997)
6 Engel, Seckel, Stanev Phys.Rev. D64 093010 (2001)

rbiting ide-angle ight-collectors

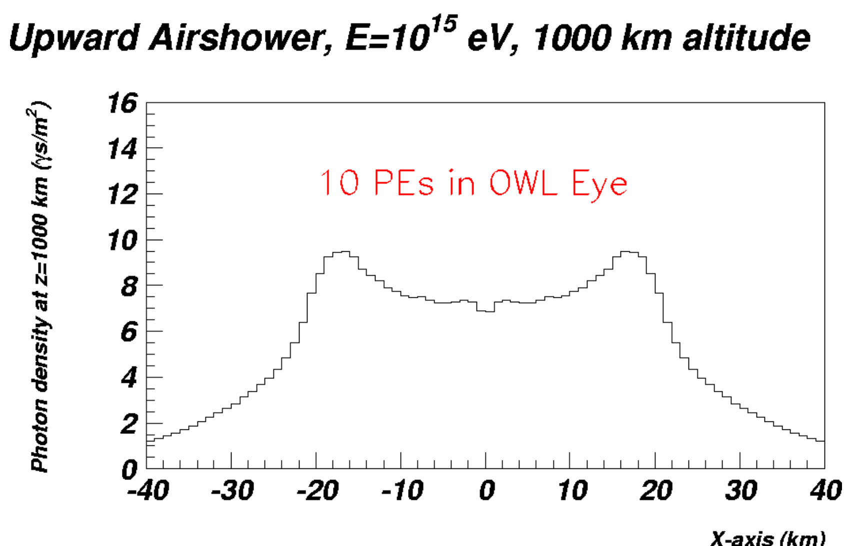
Tau Neutrino Regeneration

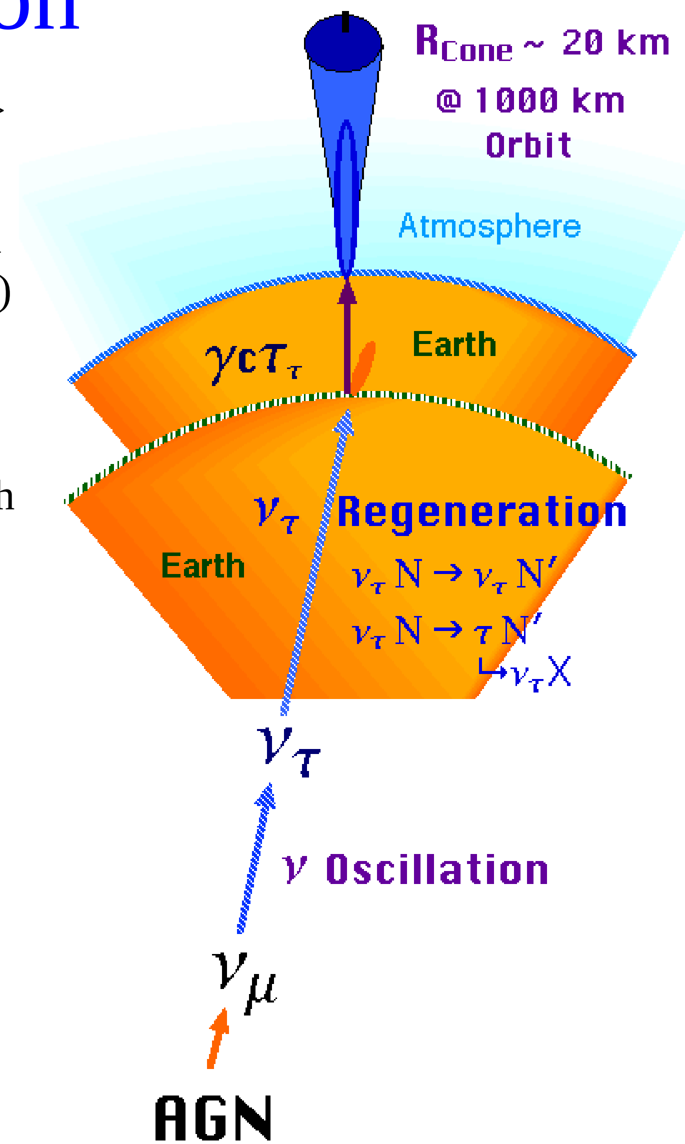
• The diameter of the Earth becomes opaque to neutrinos for E > 40 TeV

• However, tau neutrinos traverse the Earth albeit with degraded energy due to regeneration (Halzen & Saltzberg (1998), PRL 81)

• Cosmological long-baseline muon -> tau neutrino oscillation appearance experiment

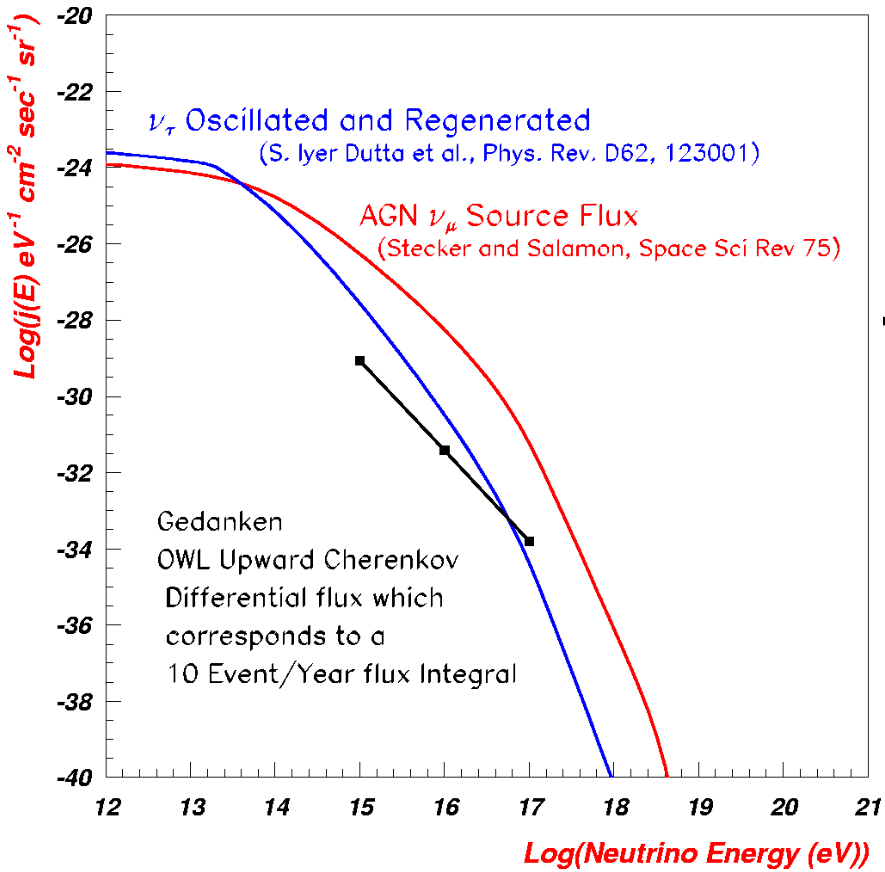
• Results of upward airshower simulation based upon Hillas with angular dispersion parameterization (J.Phys. G: Nucl.Phys 8, 1982; verified D. Kieda, ICRC Hamburg)





Directional Cherenkov radiation from upward airshowers → ~ 10^{15} eV threshold neutrino energy

Upward Airshower Flux Sensitivity



The Earth's crust is a huge neutrino target

(Ice Cube:

1 km^3 of ice ~ 10^{10} ton-ster ν Aperture

E_ν^{Thres} ~ 1 TeV)

Tau Energy	$\gamma c \tau_\tau$	***Effective*** † **ν Aperture**
10^{14} eV	5 m	10^{9} ton-ster
10^{15} eV	50 m	10^{10} ton-ster
10^{16} eV	500 m	10^{11} ton-ster
10^{17} eV	5 km	~ 10^{12} ton-ster

† 10% Duty Factor Included

Upward Airshower Signal Detection

Cherenkov signal delivered in $\lesssim$ 100 ns

Dark sky UV background 400 γ/(ns m^2 ster) $\rightarrow$ 0.2 PE/μs in each OWL pixel

Prob(PE $\geqslant$ 10| 0.2) = 2.3 x 10^{-14} Prob(PE $\geqslant$ 20| 0.2) = 3.6 x 10^{-33}

For 1 year observation time at 10% duty cycle with one instrument

5×10^5 pixels x 10^6 μs/s x π x 10^7 s/year x 0.1 x 2.3 x 10^{-14} = 36,000 accidentals (PE $\geqslant$ 10)

… x 3.6 x 10^{-33} = ~ 10^{-14} accidentals (PE $\geqslant$ 20)

Using 2 satellites separated by ~ 10 km viewing same area $\rightarrow$ ~ 10^{-9} accidentals (PE $\geqslant$ 10)

~ 10^{-47} accidentals (PE $\geqslant$ 20)

However, 0.1 Hz/cm^2 cosmic ray rate $\rightarrow$

~ 10^{10} pixel hits/year observation time (single instrument)

(0.1 Hz/cm^2 x 0.09 cm^2 x π x 10^7 s/year x 0.1 x 5 x 10^5 pixels)

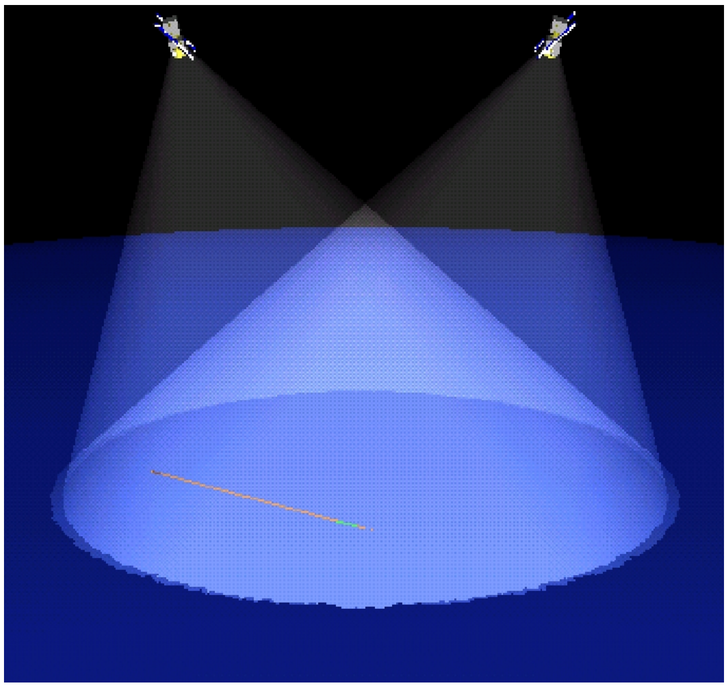
~ 25 ground-position corresponding pixel hits/year observation time (two instruments)

(2 x (0.1 Hz/cm^2 x 0.09 cm^2)^2 x 10^{-7} s x π x 10^7 s/year x 0.1 x 5 x 10^5 pixels)

Requires further rejection power (single characteristics?)

Summary

OWL will make high quality and statistics measurements of the UHECR with E $\gtrsim 3 \times 10^{19}$ eV (550 km orbits)



Above 10^{20} eV, large observing aperture (1000 km orbits) yields

- 2300 Events/Year ($E^{-2.75}$ extrapolation)
- 750 Events/Year (E^{-3} extrapolation)
- Energy reach to ~ 10^{22} eV
- Ability to measure neutrinos from `top-down' processes
- Potential for other neutrino measurements
    - Strongly interacting neutrinos

OWL is feasible with current technology

rbiting ide-angle ight-collectors